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13. ABSTRACT *(Maximum 200 words)*

This research program consists of experimental and theoretical investigation of several recently observed novel nonlinear optical phenomena occurring in liquid crystal optical fibers and fiber arrays, and to explore their possible applications in fast all-optical switches, limiters, modulators, phase conjugator, and optical storage.This research program has addressed the following problems:- (i) fabrication of isotropic liquid crystals cored optical fibers and thin films of aligned nematic liquid crystals. (ii) Use of special dopants such as dyes and Fullerene C60 were used in conjunction with bias field create molecular realignment and modify the nonlinear electro-optical responses of the liquid crystal cells. (iii) detailed characterization of the optical, and nonlinear optical properties of these liquid crystalline optical elements including propagation mode structures, transmission, nonlinear optical mechanisms in the nanosecond and shorter time regime; (iv) detailed studies of optical limiting, stimulated scatterings, phase conjugations, nonlinear absorption, photoconductivity and photorefractivity in these liquid crystal fibers.

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Final Report

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Author: Iam-Choon Khoo

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Table of Content

1. Statement of the Problems Studied

This research program consists of experimental and theoretical investigation of several recently observed novel nonlinear optical phenomena occurring in liquid crystal optical fibers and fiber arrays, and to explore their possible applications in fast all-optical switches, limiters, modulators, phase conjugator, and optical storage.

This research program has addressed the following problems:- (i) fabrication of isotropic liquid crystals cored optical fibers and thin films of aligned nematic liquid crystals. (ii) Use of special dopants such as dyes and Fullerene C60 were used in conjunction with bias field create molecular realignment and modify the nonlinear electro-optical responses of the liquid crystal cells. (iii) detailed characterization of the optical, and nonlinear optical properties of these liquid crystalline optical elements including propagation mode structures, transmission, nonlinear optical mechanisms in the nanosecond and shorter time regime; (iv) detailed studies of optical limiting, stimulated scatterings, phase conjugations, nonlinear absorption, photoconductivity and photorefractivity in these liquid crystal fibers.

2. Technical Results Obtained:

2.1 Summary:-

All the major proposed studies were successfully completed, and we have made several 'first time' observations. The publications listed in later section of this report describe these findings in more details. The following is a summary of the principal results obtained:-

- i Identified several isotropic liquid crystals suitable for use as nonlinear fiber core material
- ii. Developed a nonlinear fiber array device for optical limiting application; demonstrated its image transmission capability and superiority over bulk films as an all-optical switching device.
- iii. Demonstrated optical limiting with nanosecond and sub-nanosecond laser pulses.
- iv. Developed quantitative theoretical modeling of two-photon absorption and nonlinear guided wave optics.
- v. Synthesized a variety of exceptionally nonlinear organic liquids suitable for use as the fiber cores in the next-generation array devices. Preliminary studies have shown that these core materials yield even lower switching/limiting thresholds.
- vi. Performed further studies of self-pumped optical phase conjugation and discovered a new nonlinear electro-optical effects in dye- or fullerene C60-doped nematic liquid crystal films. Developed a quantitative theory for the photorefractive effect discovered.
- vii. Filed two patent applications, one on the fiber array and one on the photorefractive effect. Both applications were approved; one patent is issued and one pending.

2.2 Technical Details:-

2.2.1 Nanosecond and picosecond laser limiting with nonlinear fiber array.

Various nonlinear optical materials and processes are being investigated for application in fast all-optical modulators, switches, limiters, fiber and other guided wave optical elements. For advanced applications such as high data rate communication, visible-IR sensor/eye protection, and optical storage, the performance characteristics required of these devices and materials are rather stringent. In eye/ sensor protection application, for example, the operation spectral bandwidth

required of the device is the entire visible spectrum; very broadband and fast all-optical or nonlinear optical means have to be employed.

We have developed liquid cored fiber arrays capable of fulfilling these practical requirements for all-optical limiting of short (nanosecond-picosecond) laser pulses. In our studies, we have also discovered several core materials that possess very broadband [~400 - 700 nm] and exceptionally large nonlinearities. In the nanosecond-picosecond time scale, the dominant nonlinear mechanisms in these new material systems [**1**] are similar to Fullerene[**2**] or Phthalocyanine[**3**] systems, namely, nonlinear absorption, excited state absorption and reverse saturable absorption effect, c.f. **Figure. 1**. In the nanosecond and longer time regime, these photo-absorption processes are followed by negative thermal/density refractive index changes and fluctuations, leading to wide angle nonlinear scattering and leaky waveguiding.

Majority of these organic molecules exhibit ordered liquid crystalline phases[**4**]. However, for fiber optics applications, the isotropic phase of these materials are preferred over the ordered phases because of the low scattering loss. The high optical nonlinearities of these isotropic-phase liquid crystals makes it possible to fabricate compact mm-thick fiber faceplates that could function as efficient optical limiters, c.f. **Figure 2**. In these thin fiber arrays, loss and image blurring by orientational fluctuation scattering in the core, and fiber crosstalk are minimized, and high quality image transmission are obtained.

The optical limiting thresholds obtained with these fiber structures are among the lowest of all the materials currently under investigation [**5**]. For examples, studies conducted with nanosecond laser pulses [λ=0.532 nm] in these fibers show that the limiting thresholds can be << 1μJ [corresponding to a focused fluence of below 0.1 Joule/cm^2 for a fiber core diameter of 30 μm], c.f. **figure 3a**.The output energy is clamped at a level < 1 μJ for incident laser energies up to the point when either a bubble is created within the focused spot or a pin-prick damage spot is created on the entrance glass window, depending on the type of glasses or core liquids used. When this occurs, typically for laser energy ~ 300 μJ [focused fluence of ~ 40 J/cm^2], the transmission of the "damaged" spot is of vanishing value. However, the overall image transmission quality of the fiber array is not affected by these pin-prick size damage spots. These fiber array devices, therefore, possess very high operating dynamic range. In conjunction with the broadband [400-700 nm] response of the core materials, these fiber arrays are therefore highly promising for developing practical devices.

Figure 3b shows recently observed results with picosecond laser pulses [λ=0.532 nm] For both LC-X doped ILC and LC-Y cored fibers, the optical limiting thresholds are $\leq$ 0.1 μJ; the clamped outputs [not shown] are also ~ 0.1 μJ, with LC-Y giving the better performance. More detailed studies of these highly promising observations are currenly being conducted, and will be further pursued in the next phase study proposed.

2.2.2. Analytical modeling of sequential nonlinear absorption, refraction, propagation and optical limiting in a nonlinear fiber.

We have developed theoretical models that allow us to describe and analyze these observed nonlinear propagation and optical limiting effects, and the underlying molecular photo-physical processes. The models account for nonlinear absorption, refraction and other molecular processes occurring in the core materials as well as the nonlinear guided wave optical phenomena.

Figure **4** depicts schematically the fiber entrance region and the guiding core and list some

of the nonlinear optical processes that could be generated by a short intense laser pulse. Because of the large index difference between the liquid crystal core and the glass cladding, and the relatively large core diameter, these fibers operate in multimodes.The light intensity distribution within the fiber core is practically uniform and is simply a function of the propagation distance z into the fiber.

The laser induced refractive index changes associated with thermal and density fluctuation and the resulting intensity dependent guided modes propagation in the nonlinear fiber core have been treated before [6]. We have recently developed a model that takes into account also the nonlinear absorption processes. To describe short laser pulse interaction, a time-dependent version of this propagation equation, and a dynamical description of the of the molecular energy level populations are also needed.

Figure 5 shows the theoretical modeling using the formalism described above for recently obtainedfor picosecond laser pulse optical limiting results. The fiber core material is ILC, which is [linearly] non-absorbing in the visible regime, but exhibit strong nonlinear absorption effects. The theoretical fit yields an effective two-photon absorption coefficient $\beta \sim 2.5$ cm/GW. On the other hand, other slightly absorbing liquids yield much larger β values in the range of 5 - 10 cm/GW, c.f. **Table 1**. Since thermal/density effects are not expected to contribute in this time regime, the optical limiting effects are all attributed to nonlinear absorption processes described above. In particular, the larger β's of the lightly absorbing liquids over the clear ones are attributed to resonance enhancement through single-photon absorption between the ground state and its high lying ro-vibrational manifold; a larger excited [electronic] state absorption coefficient [7] could also be a contributing mechanism.Quantitative studies and measurements are clearly in order, and will be pursued in the next-phase study.

In **Table 1,** the effective two-photon absorption coefficients for several cored materials are summarized. The values are all significantly larger than previously reported results for bulk isotropic liquid crystals [bottom half of Table 1]. The use of the fiber geometry [versus the bulk], as well as the special core materials developed in our program are the principal reasons for the much larger effective nonlinear absorption coefficients and lower limiting thresholds and clamping levels.

2.2.3 Photoconductivity and photorefractivity of nematic liquid crystals

We have recently observed large photoconductivity and by far the largest photorefractivity in Fulerene C_{60} and its derivatives -doped nematic liquid crystal films. The effects are more pronounced than those previously reported [8,9]. The effects can be generated in planar or homeotropic aligned nematic films, for various optical field-nematic film interaction configurations. A combination of small ac and dc applied fields enables pretilting of the liquid crystal axis and its subsequent modulation, leading to enhanced grating diffraction efficiency as well as the speed of writing.

Figure 6 shows one of the liquid crystal-applied fields configurations used. The nematic liquid crystal can be any of the commercially available ones such as 5CB or E7 [1,2]. We have studied dopants ranging from various laser dyes [R6G, Methyl Red] dichroic dyes, C_{60} or a C_{61} derivatives PCBM (1-(3-methoxycarbonyl)propyl-1-phenyl-[6,6]-C_{61}). Planar alignment is achieved by rubbing the PVA polymer coating of the glass windows, whereas homeotropic alignment is created with surfactant treatment [1]. Typical sample thickness used is ~ 25 microns. The glass windows are coated with transparent ITO electrodes for applying dc and or ac bias fields. Various laser lines of an Argon laser have been used. Typically, the laser power used in each writing beam is about 10 mW, with beam diameters around 4 mm. The applied dc voltage

required to see large observable diffraction effect is around 1-volt, c.f., **Figure 7**. Under these applied field strengths, a multi-order forward diffraction pattern is observed; visible 4th or 5th order diffractions are routinely obtained. The first order diffraction efficiency can be as high as 30 % for the R6G- or C_{60}-doped amples. Using the C_{61} derivative, the same effects can be observed with an optical writing beam power of ≤ 1 mW.

The dynamics of the grating formation process in these fullerene-doped nematic films is similar to that described in reference [**8**]. If the laser and applied field duration is short, the grating is transient in nature. On the other hand, if the applied optical and/or bias fields are more intense, or if the interaction is prolonged, the grating assumed a permanent component. The effect is attributed to molecular axis reorientation caused by the combination of an applied dc field and the optically induced dc space charge fields. Flows and some hitherto undetermined electro-chemical or photo-chemical processes may also contribute to the permanent grating formation process. Three mechanisms for space charge field formation have been identified:- the usual photorefractive effects, and the Carr-Helfrich effect associated with the liquid crystal's dielectric and conductivity anisotropies [**8**].

An interesting and useful feature of these permanent holographic gratings written in nematic films is that they can be turned on and off with an applied ac field via the usual linear electro-optical effect [**1,2**]. An ac voltage [Vpp >40 Volt] at 200 Hz will completely realign the nematic director axis throughout the whole sample, and thus turn off the grating. This occurs within a time scale of 100 microseconds. When the ac field is removed, the grating recovers in about 10 milliseconds. Use of ac fields at intermediate strengths, at frequency in the range of 1-1000 KHz has also been shown to be a possible means for enhancing the grating diffraction efficiency, c.f. **Figure 8**. This is attributed to different frequency dependence of the dielectric anisotropy for the illuminated region from the background.

Consider thenonlinear sensitivity S, defined by S=dn/F [where dn is the induced index modulation and F is the incident laser energy fluence in units of energy/area] in comparison to other photorefractive materials [**10**]. We have previously shown that a value of S~ 5×10^{-5} cm^2/Joule can be easily achieved with C_{60}-doped films. Using the C_{61}-derivative, we found that the photoconductivity can be improved by about two orders of magnitude, and the nonlinear sensitivity of the resultant nematic liquid crystal films can be > 10^{-3} cm^2/Joule. Nematic liquid crystals are therefore highly competitive in comparison with other photorefractive crystals, polymers or doped glasses [**10**]. Because of the broadband (0.4 mm - 6 mm) birefringence and transparency of nematic liquid crystals [**1,2**], the possibility of fabricating multi-film stacks and "solid-state" polymer dispersed liquid crystalline films, the observed effects are promising candidate for applications in light valves, spatial modulators, holographic storage, beam/image steering and processing systems.

2.3 Conclusions and recommendation:

The fiber array device concept, and the unusually nonlinear fiber core materials developed in our program are highly promising for practical device implementation. Optical limiting is but one of several nonlinear optical processes stemming from the nonlinear optical responses of the core molecules. It is clear that these fast electronic-origin nonlinear responses could also be utilized for devising fast all-optical switches, interconnecting element, gates, directional couplers and soliton generation. Stimulated Raman and Brillouin scattering have been observed previously in liquid crystals fibers and bulk films , and could be used for frequency conversion and phase conjugation purposes .Solid state liquid crystalline cored fibers could also be fabricated by mixing the liquid crystals and curing with optical polymer.

These new findings pose several new challenging fundamental questions on fiber nonlinear optics, and the photophysics of the complex molecular systems that form the fiber core. We have submitted a renewal proposal for a multi-prong program of study centered on:- (i) Nonlinear optics and optical physics of isotropic liquid crystals and organic liquids and their composites with C60 derivatives and other molecular systems with large excited state absorption coefficients (ii) Fabrication of new fibers and fiber array structures and quantitative studies of guidedwave nonlinear optical phenomena and their applications.

3. Publications:-

3.1 Books:

1. I. C. Khoo, "Liquid Crystals: Physical Properties and Nonlinear Optical Phenomena" [Wiley Interscience, NY 11/94]

2. I. C. Khoo,F. Simoni and C. Umeton, ed. "Novel Optical Materials and Applications" [Wiley Interscience, NY 10/96]

3.2 Refereed Journals and Proceedings:

1. Nonlinear optical propagation and self-limiting effect in liquid crystalline fiber. I. C. Khoo and H. Li, Appl. Phys. B, 59, p. 573 (1994).

2. Self-starting phase conjugation with cross-polarization stimulated orientational scattering in liquid crystal. I.C. Khoo and Yu Liang, Optics Letters, 20, 130 (1995).

3. Holographic grating formation in dye- and fullerene C_{60}-doped nematic liquid crystal film. I. C. Khoo, Optics Letters, 20, 2137 (1995).

4. All Optical switching of infrared optical radiation using isotropic liquid crystals. P. G. LoPresti, P. Zhou, R. G. Lindquist and I. C. Khoo, IEEE J. Quantum Electronics, JQE 31, pp. 723 (1995).

5. Nonlinear optical phenomena in fullerene-doped liquid crystal films and fibers. I.C. Khoo, H. Li, Y. Liang, Ming Lee, B. Yarnell, K. Wang and M. Wood, Invited paper, Fullerene and Photonics II, SPIE , 2530 (1995).

6. Liquid crystal photorefractivity for recording holographic gratings. I.C. Khoo, Invited paper in '*Liquid Crystals, Devices, and Applications*', IS&T/SPIE, Vol 2651 (1996).

7. Optical limiting with liquid crystalline cylindrical guided wave optical elements. I.C. Khoo, H. Li, Ming Lee, B.K. Yarnell and M.V. Wood in '*Materials for Optical Limiting*' Material Research Society Proceedings, 374 (1995), ed. R. Crane, K. Lewis, E.V. Stryland and M. Khoshnevisan.

8. Optical-dc-field induced space charge fields and photorefractive-like holographic grating formation in nematic liquid crystals. I.C.Khoo. Molecular Crystal Liquid Crystals, 282, pp. 53-66 (1996).

9. Fullerene-doped liquid crystal fiber and fiber array for all-optical switching. I .C. Khoo, in '*Novel Optical Materials and Applications*' ed. I. C. Khoo, F. Simoni and C. Umeton (Wiley Interscience, NY 10/1996].

10. Orientational photorefractive effects in nematic liquid crystal film. I. C. Khoo . IEEE J. Quantum Electronics JQE 32, pp. 525-534 (1996).

11. Isotropic liquid crystal fiber structures for optical limiting of nanosecond and picosecond laser pulses.M. V. Wood, Brett D. Guenther and i. C. Khoo. Invited Paper in "Nonlinear Optical Liquids" SPIE -Int. Society for Optical Engineering. Denver, Co. 8/1996. Proceeding Vol. in print.

12. Nonlinear Liquid Crystal Fiber Structures for Passive Optical Limiting of Short Laser Pulses. I. C. Khoo, M. V. Wood, M. Lee and Brett D.Guenther. Optics Letters 21, 1625-1627 (1996).

3.3 Conference Presentations:-

1. Low power visible-near infrared (0.4μm-5μm) self-starting phase conjugation with liquid crystal. I. C. Khoo, Y. Liang and H. Li. IEEE Nonlinear Optics '94, Hawaii (July 1994).

2. Nonlinear photorefractive effects in liquid crystals. I. C. Khoo, H. Li, and Y. Liang. IEEE Lasers and Electro-Optics Society Annual Technical Meeting, Boston (October 1994).

3. Photorefractive liquid crystals. I. C. Khoo. Invited paper. First Air Force Workshop on Photorefractive Materials, Wright Patterson AFB, Ohio (August 1996).

4. Photorefractivity, two beam coupling and holographic recording in dye-, fullerene-doped nematic liquid crystal film. I. C. Khoo, H. Li, Y. Liang, M. Lee, B. Yarnell, K. Wang, and M. Wood. Conference on Lasers and Electronics, Baltimore (May 1995).

5. Liquid crystal fiber arrays for image transmission and all-optical switching and limiting application. I. C. Khoo, M. Lee, M. Wood and K. Wang. IEEE/LEOS Annual Technical Meeting, San Francisco, CA (November 1995).

6. Nonlinear electro-optical holographic storage effects in fullerene C_{60}-doped nematic liquid crystal films. I. C. Khoo, K. Wang, M. Wood and M. Lee. IEEE/LEOS Annual Technical Meeting, San Francisco, CA (11/1995).

7. Nonlinear optical phenomena in fullerene-doped liquid crystal films and fibers. I. C. Khoo, H. Li, Y. Liang, M. Lee, B. Yarnell, K. Wang and M. Wood. Invited paper. "Fullerene and Photonics" SPIE Int. Science, Engineering, and Instrumentation Symposium, San Diego (July 1995).

8. Photorefractivity and storage holographic gratings in dye- and fullerene-doped nematic liquid crystal film. I. C. Khoo. Invited paper. SPIE Int. Science, Engineering, and Instrumentation Symposium, San Diego (July 1995).

9. Optical-dc-field induced space charge fields and photorefractive-like holographic grating formation in nematic liquid crystals. I. C. Khoo. Invited paper. Int. Topical Meeting on Optics of Liquid Crystals. Le Touquet, France (9/1995).

10. Optical Limiting with Liquid Crystalline Cylindrical Guided Wave Optical Elements. I.C.Khoo. Invited Paper in "Materials for Optical Limiting"-Material Research Society Fall Meeting, Boston, 11/95

11. Liquid crystal fiber and fiber array for all-optical switching. I. C. Khoo. Invited paper. International Micro-Optics Conference, Hiroshima, Japan (November 1995).

12. Liquid crystal photorefractivity for recording holographic gratings. I. C. Khoo. Invited paper. IST/SPIE Electronics Imaging Symposium, San Jose, CA (January 1996).

13. Photorefractivity and holographic storage effects in nematic liquid crystals. I. C. Khoo. Invited Paper. Liquid Crystals for Advanced Technologies - Material Research Society Spring '96 Meeting, San Francisco, CA.

14. Liquid crystal fiber arrays for image transmission and all-optical switching and limiting application. I. C. Khoo, M. Lee, K. Wang and M. Wood. Conference on Lasers and Electro-Optics. Anaheim, CA (July 1996). CLEO '96-Technical Digest, p181.

15. Nonlinear liquid crystal optical fiber array. I. C. Khoo, M. Lee, K. Wang, M. V. Wood and Brett D. Guenther. Nonlinear Optics, Hawaii (July 1996).

16. Isotropic liquid crystal fiber structures for optical limiting of nanosecond and picosecond laser pulses.M. V. Wood, Brett D. Guenther and I. C. Khoo. Invited Paper in "Nonlinear Optical Liquids" SPIE -Int. Society for Optical Engineering. Denver, Co. 8/1996.

17. Isotropic [Liquid] Liquid Crystal Fiber Array for Optical Switching/Limiting. I. C. Khoo, M. V. Wood and Brett. D. Guenther. Invited paper - IEEE-LEOS '96 Annual Meeting, Boston, 11/96.

4. Report of Invention:

Patents:-

(i) U. S. Patent # 5,552,915 - issued in Sept. 1996
"Liquid Crystal Nonlinear Photorefractive Electro-Optical Storage Device Having a Liquid Crystal Film Including Dopant Species of C_{60} and C_{70}"

(ii) U.S. Patent Application Filed April 1995.
"Liquid Crystal Fiber Array for Optical Limiting of Laser Pulses and For Eye/Sensor Protection" - Application approved in June 1996; patent issuance pending.

5. Participating Scientific Personnel:

The program involves the principle investigator and a few Ph. D. graduate students [H. Li, Y. Liang and recently Michael Wood and P. Chen] under the direction of the principal investigator at various stages of this program. Both H. Li and Y. Liang finished their Ph. D. degree studies and graduated in 1995. Michael Wood is a senior Ph. D. student and has passed the Ph. D. candidacy examination and P. Chen is a second year graduate students.

6. References:-

1. I. C. Khoo, M. V. Wood and Brett D. Guenther, Opt. Letts.21, 1625-1627 (1996)
2. See for example, K. M. Nashold and D. P. Walter, J. Opt. Soc. Am B12, pp1228-1237 (1995) and references therein.
3. See for example, J. S. Shirk, Richard G. S. Pong, F. J. Bartoli and A. W. Snow, Appl. Phys. Letts. 63, 1880 (1993) and references therein.

4. I. C. Khoo, "*Liquid Crystals: Physical Properties and Nonlinear Optical Phenomena*", [Wiley Interscience, NY, 1994].I. C. Khoo and S. T. Wu, "*Optics and Nonlinear Optics of Liquid Crystals*," [World Scientific, Singapore 1993]
5. See, for example, materials featured in "*Materials for Optical Limiting*", ed. R. Crane, K. Lewis, E. Van Stryland and M. Khoshnevisan [Material Research Society Proceedings Vol. 374, 1995].
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7. F. W. Deeg and M. D. Feyer, J. Chem. Phys. 91, 2269 (1989); H. J. Eichler, R. Macdonald and B. Trosken, Mole. Cryst. Liq. Cryst. 231, 1 (1993).
8. I. C. Khoo, Opt. Letts. 20, 2137 (1995); I. C. Khoo, IEEE J. Quant. Electronics JQE 32, 525-534 (1996). U. S. Patent Number : 5552915 [issued Sept. 3, 1996]
9. E. V. Rudenko and A. V. Sukhov, JETP Lett. 59, 142 (1994); JETP 78, 675 (1994)
10. See, for example, A. Partovi, T. Erdogan, V. Mizrahi, P. J. Lemaire, A. M. Glass and J. W. Heming, Appl. Phys. Lett. 64, 821 (1994).

7. List of illustrations attached

A total of 8 figures and 1 table, and 2 additional illustrative notes are attached:-

Figures/table [referred to in section 2]:-

Table 1: Comparison of effective two-photon absorption coefficients β

Fig.1 Schematic depiction of two-photon, sequential, and excited absorption processes, intersystem crossing, and other molecular processes induced by a short laser pulse in the nonlinear fiber core material.

Fig.2 Schematic of the side and front views of the fiber array device for optical limiting application. The opaque glass cladding will absorb the leaky waveguide modes resulting from thermal/density refractive index change in the core. The nonlinear guiding core will attenuate high energy laser pulses through a variety of nonlinear absorption processes.

Fig.3a Output versus input energies of the nonlinear liquid cored fiber for nanosecond laser pulses [λ=0.532 mm; pulse width = 20 ns]. Fiber length =5 mm; core diameter = 30 μm. Thresholds and clamping levels for C60-doped ILC and LC-Y are $\leq$ 0.5 μJ and 1 μJ, corresponding to fluence of 0.05 J/cm^2 and 0.1 J/cm^2 in optical system with gain of 10^5, respectively.

Fig.3b Typical observed output versus input picosecond [66ps FWHM] input laser pulse energies through an isotropic liquid crystal LC-X doped ILC cored fiber [length: 5 mm; core diameter: 30 μm]. Also plotted are the transmission as a function of the input laser pulse energy for LC-X doped ILC and LC-Y fiber cores. Insert are the molecular structures of LC-X and LC-Y.

Fig.4 Nonlinear Optical processes at the entrance and guiding core region.

Fig.5 Picosecond laser pulse limiting effect through fiber with ILC core for fiber lengths of 3mm, 5mm and 7mm. Core diameter=30 μm. Core material: a commercial isotropic cholesteric liquid crystal. Linear absorption coefficient α_a: 2 cm^{-1}. The solid curves are theoretical fit using a model that accounts for linear and two-photon absorption.

Fig.6 Schematic depiction of the construction of a planar aligned nematic liquid crystal film and the interaction geometry for the applied bias fields and the incident optical writing beams.

Fig.7 Self diffraction efficiency as a function of the ac field for various dc bias voltages. Above the ac field induced Freedericksz transition, the diffraction reaches a maximum that depends on the dc bias voltage.Sample used is C_{60} doped Pentyl-Chloro-Biphenyl [5CB] film.

Fig.8 AC bias field frequency dependence of the diffraction efficiency from the permanent grating generated in a C60-doped nematic liquid crystal film.

8. Appendix - Table, Figures, Illustrations

Table 1: Comparison of *effective two-photon absorption coefficients* β

Materials	Effective β [in cm/GW]	
[This study]		
Fiber		
ILC	~ 2 [66 ps]	~10 [20 ns]**
ILC+ LC-X	~ 5 [66 ps]	~30 [20 ns]**
ILC + LC-Y	~ 10 [66ps]	~50 [20 ns]**
ILC + C60	~ 5 [66 ps]	~50 [20 ns]**

**[contributions from thermal/density effects are responsible for these extremely large values obtained for the nanosecond time regime]

Bulk [see ref. * below]		
*CS_2	small	
*ETBBA		
*IPBBA		
*BBIPA	~0.55 [30 ps]	
*PEBBA		
*MEBBA		

* M. J. Soileau, E. W. Van Stryland, G. Guha, E. J. Sharp, G. L. Wood and J. L. W. Pohlman, Mole. Cryst. Liq. Cryst. 143, 139-143 (1987).

Fig.1 Schematic depiction of two-photon, sequential, and excited absorption processes, intersystem crossing, and other molecular processes induced by a short laser pulse in the nonlinear fiber core material.

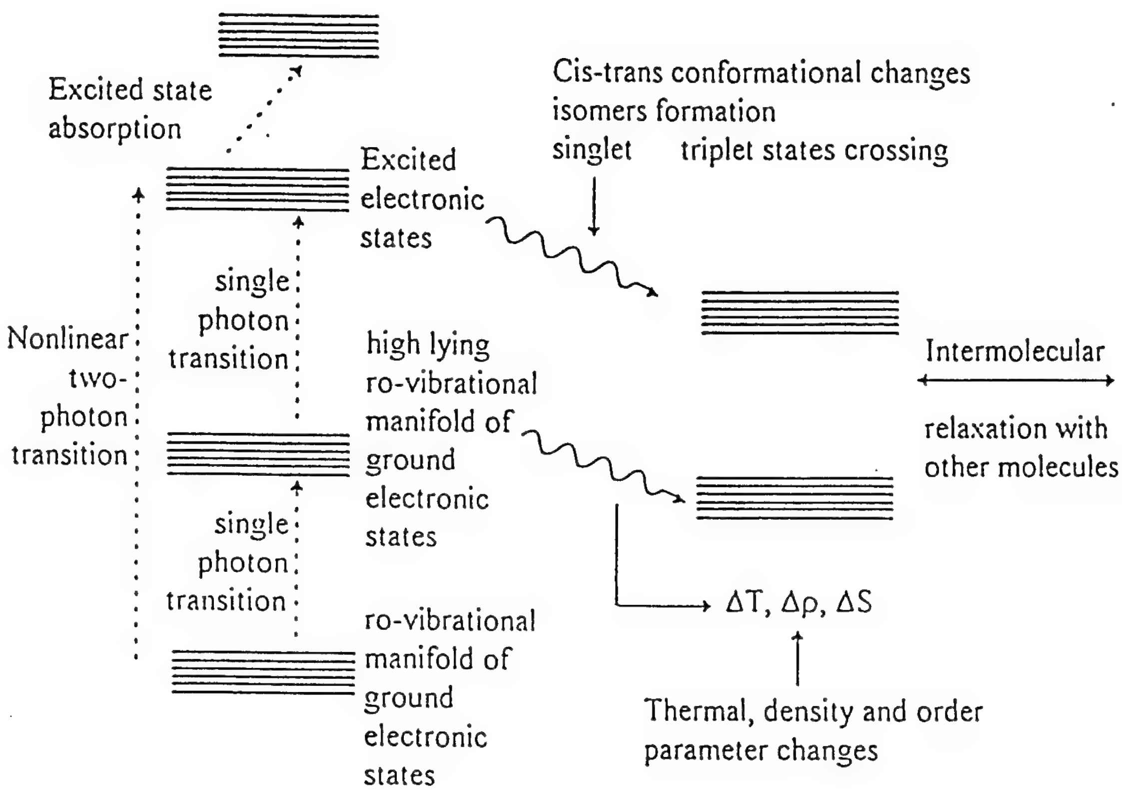


Fig.2 Schematic of the side and front views of the fiber array device for optical limiting application. The opaque glass cladding will absorb the leaky waveguide modes resulting from thermal/density refractive index change in the core. The nonlinear guiding core will attenuate high energy laser pulses through a variety of nonlinear absorption processes.

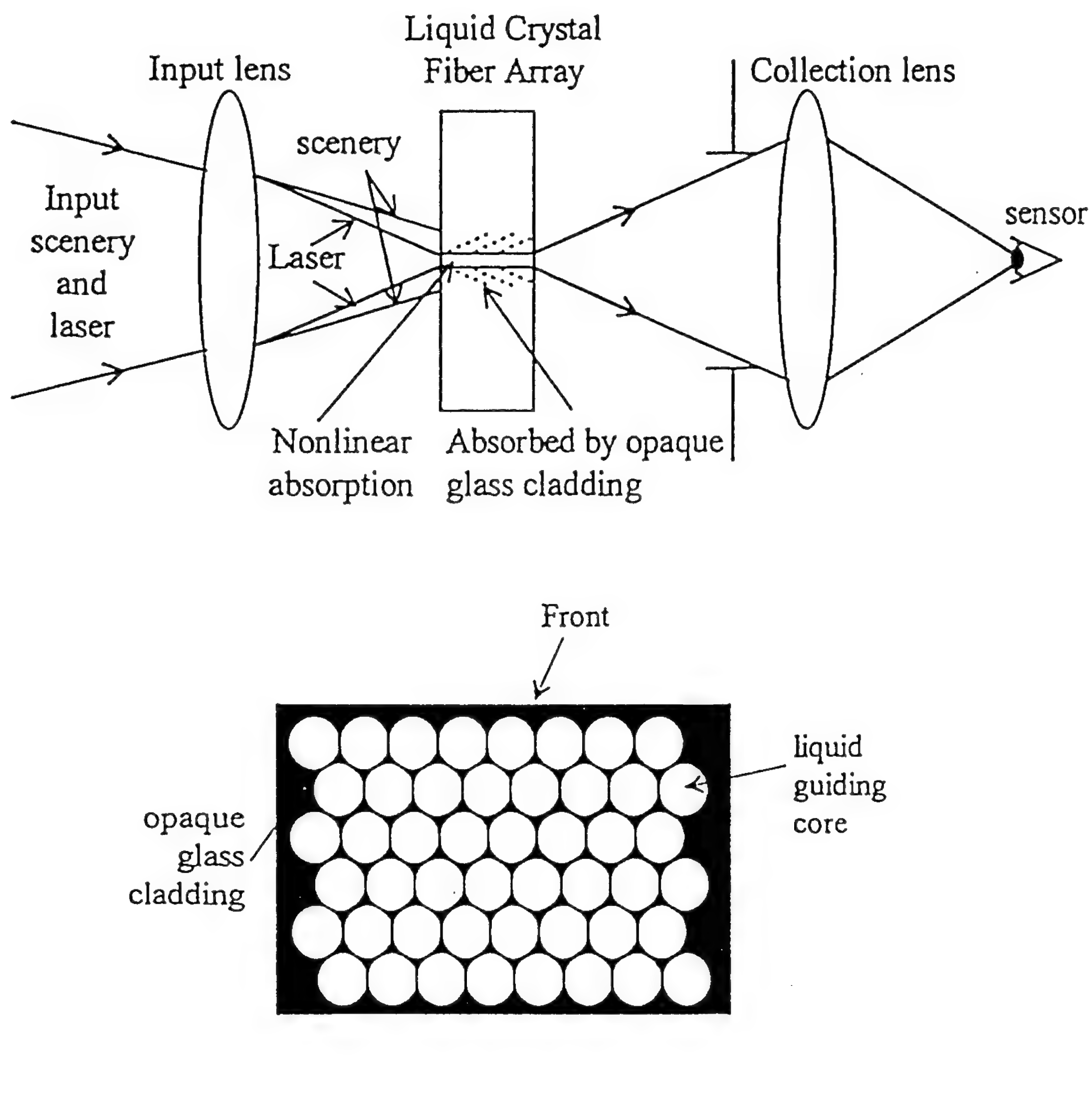


Fig.3a Output versus input energies of the nonlinear liquid cored fiber for nanosecond laser pulses [λ=0.532 mm; pulse width = 20 ns]. Fiber length =5 mm; core diameter = 30 μm. Thresholds and clamping levels for C60-doped ILC and LC-Y are ≤ 0.5 μJ and 1 μJ, corresponding to fluence of 0.05 J/cm^2 and 0.1 J/cm^2 in optical system with gain of 10^5, respectively.

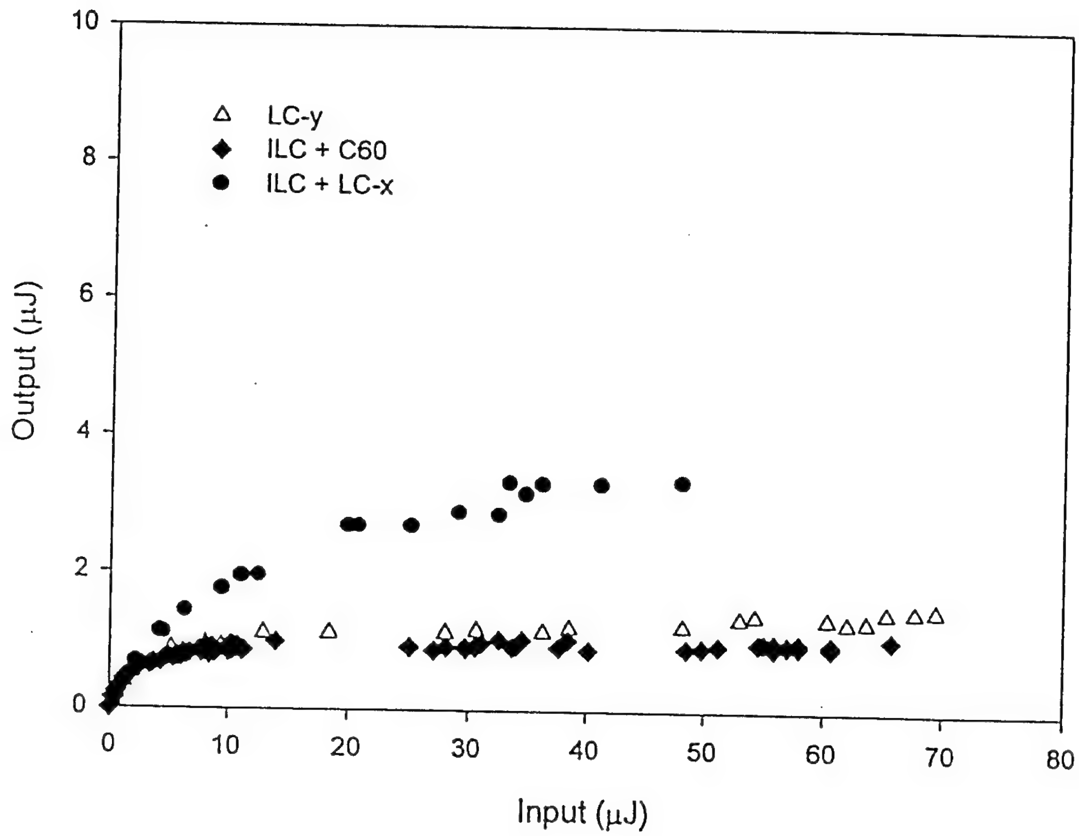
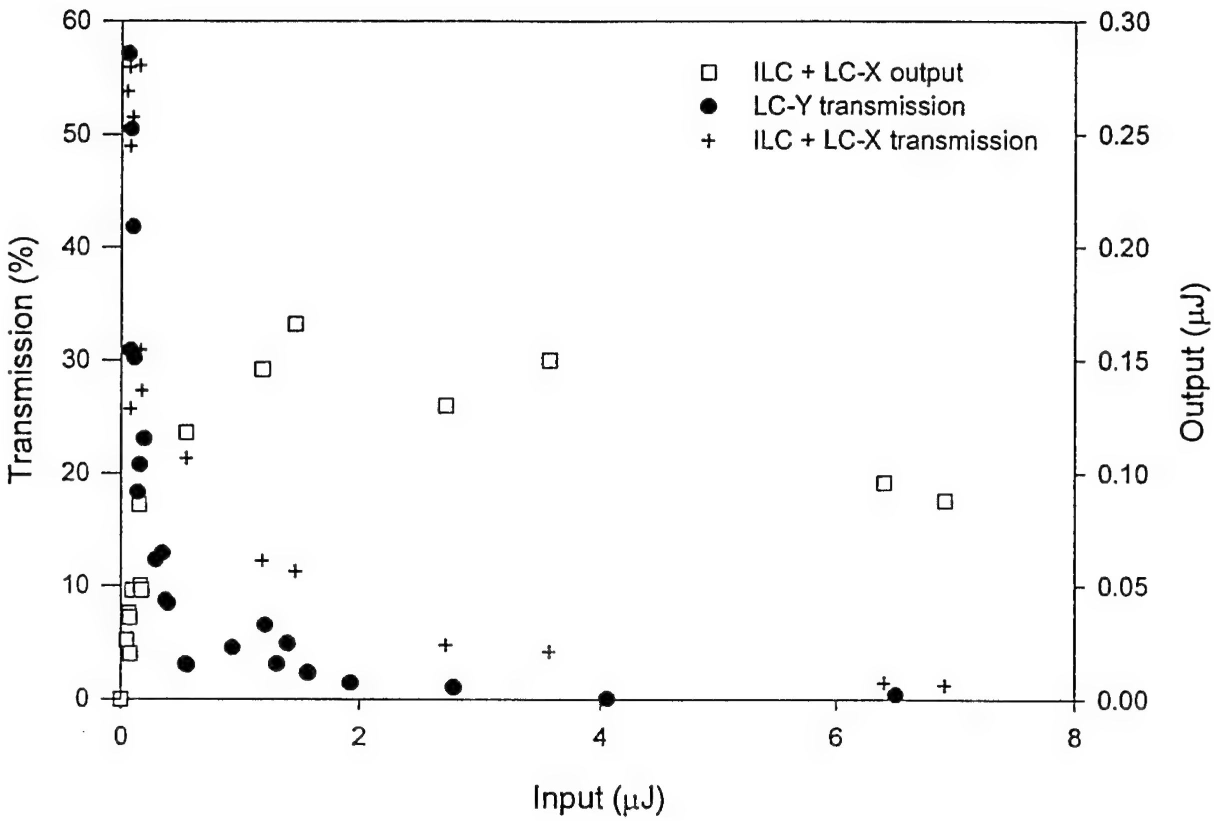
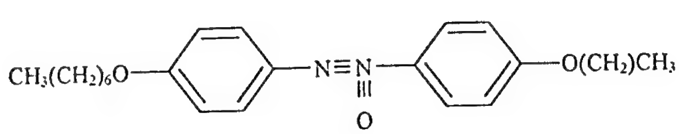
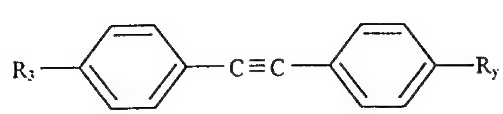


Fig.3b Typical observed output versus input picosecond [66ps FWHM] input laser pulse energies through an isotropic liquid crystal LC-X doped ILC cored fiber [length: 5 mm; core diameter: 30 μm]. Also plotted are the transmission as a function of the input laser pulse energy for LC-X doped ILC and LC-Y fiber cores. Insert are the molecular structures of LC-X and LC-Y.





LC-x [4-4' -Bis (heptoxyl) azoxybenzene



LC-Y [C3PhCCPhCy]

Fig.4 Nonlinear Optical processes at the entrance and guiding core region.

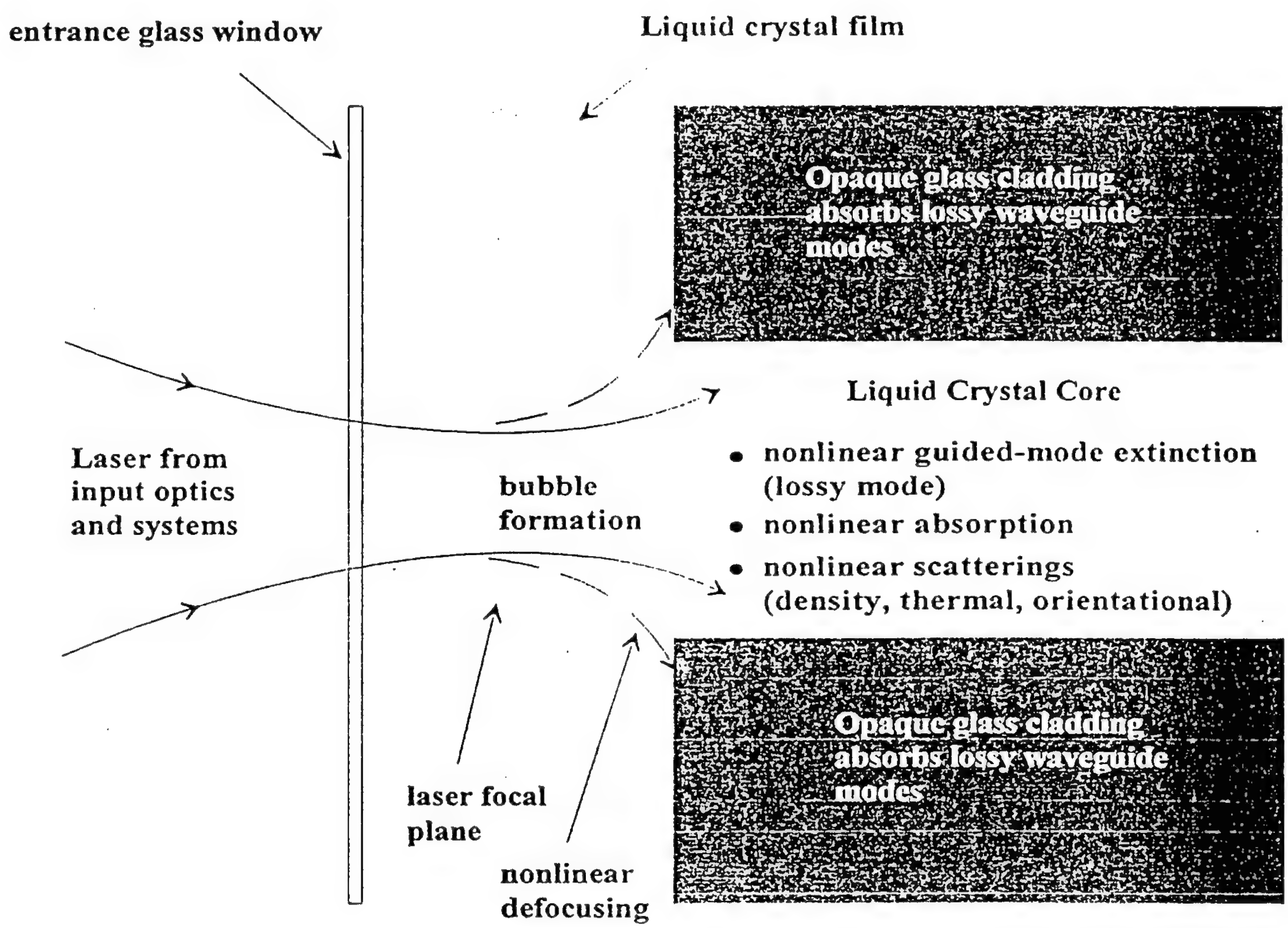


Fig.5 Picosecond laser pulse limiting effect through fiber with ILC core. for fiber lengths of 3mm, 5mm and 7mm. Core diameter=30 μm. Core material: a commercial isotropic cholesteric liquid crystal. Linear absorption coefficient α_a: 2 cm^{-1}. The solid curves are theoretical fit using a model that accounts for linear and two-photon absorption.

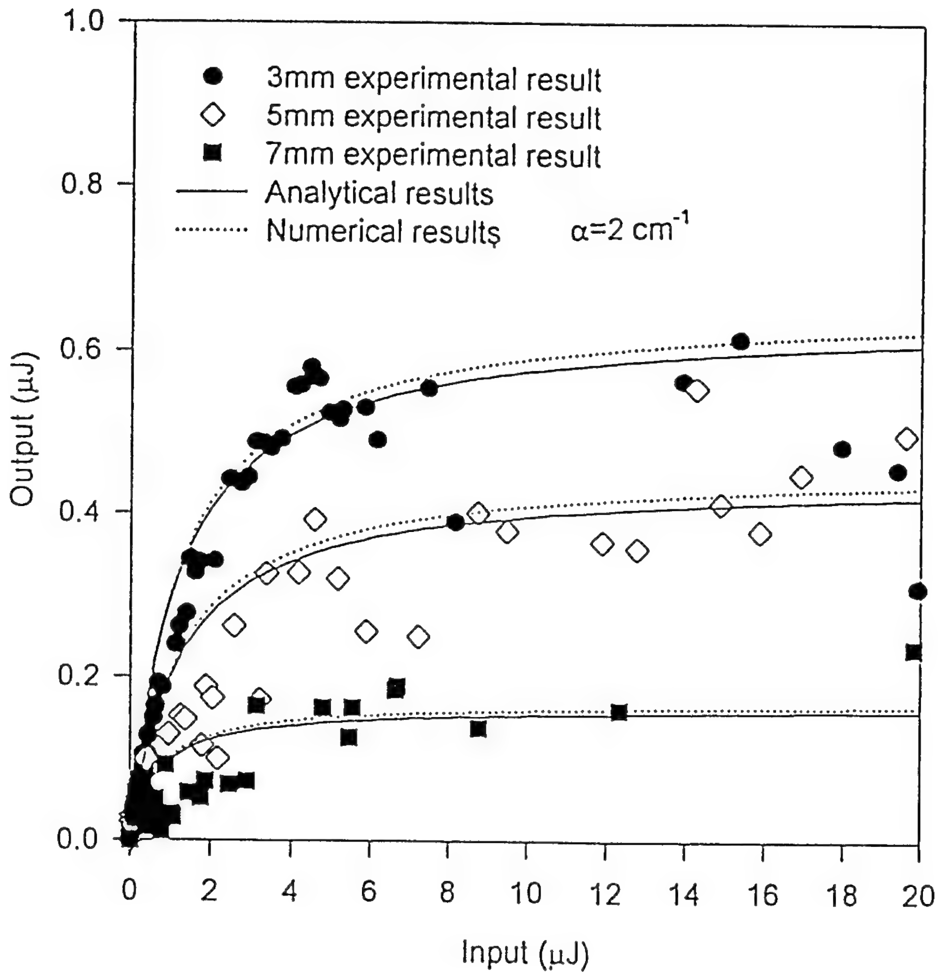
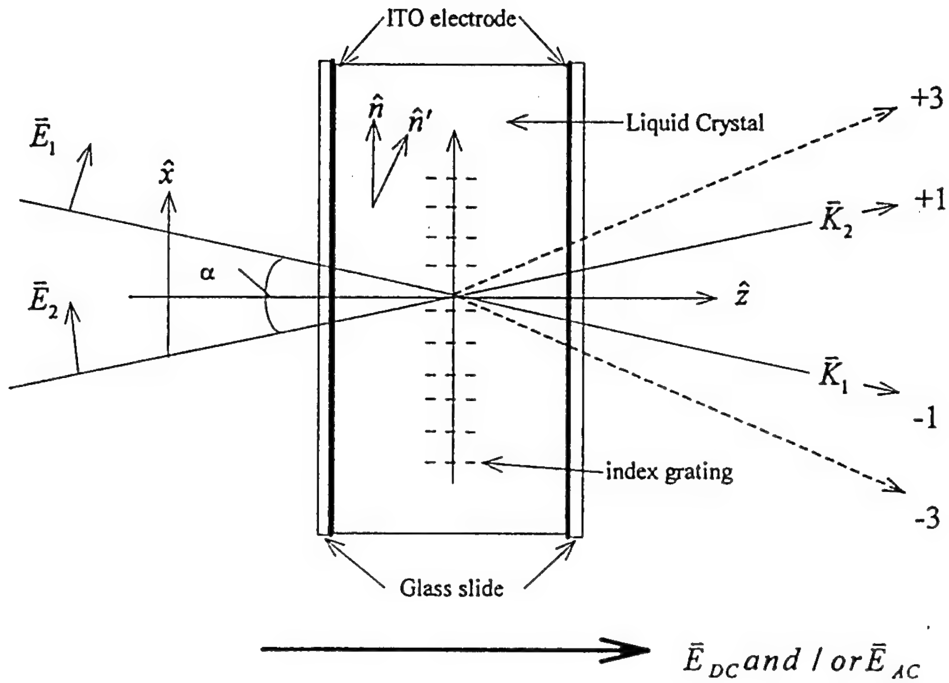


Fig.6 Schematic depiction of the construction of a planar aligned nematic liquid crystal film and the interaction geometry for the applied bias fields and the incident optical writing beams.



Planar Aligned Self Diffraction Schematic

Fig.7 Self diffraction efficiency as a function of the ac field for various dc bias voltages. Above the ac field induced Freedericksz transition, the diffraction reaches a maximum that depends on the dc bias voltage. Sample used is C_{60} doped Pentyl-Chloro-Biphenyl [5CB] film.

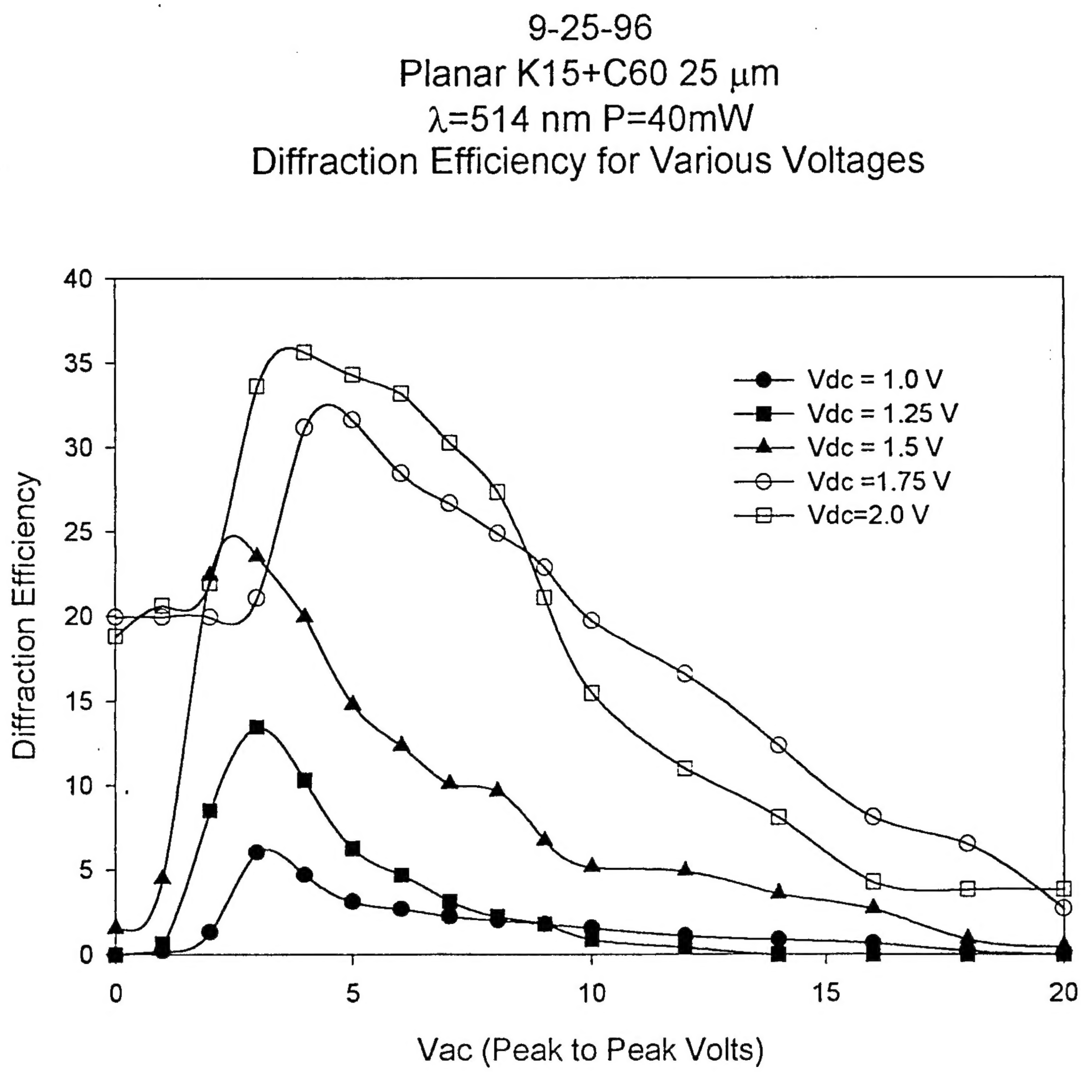
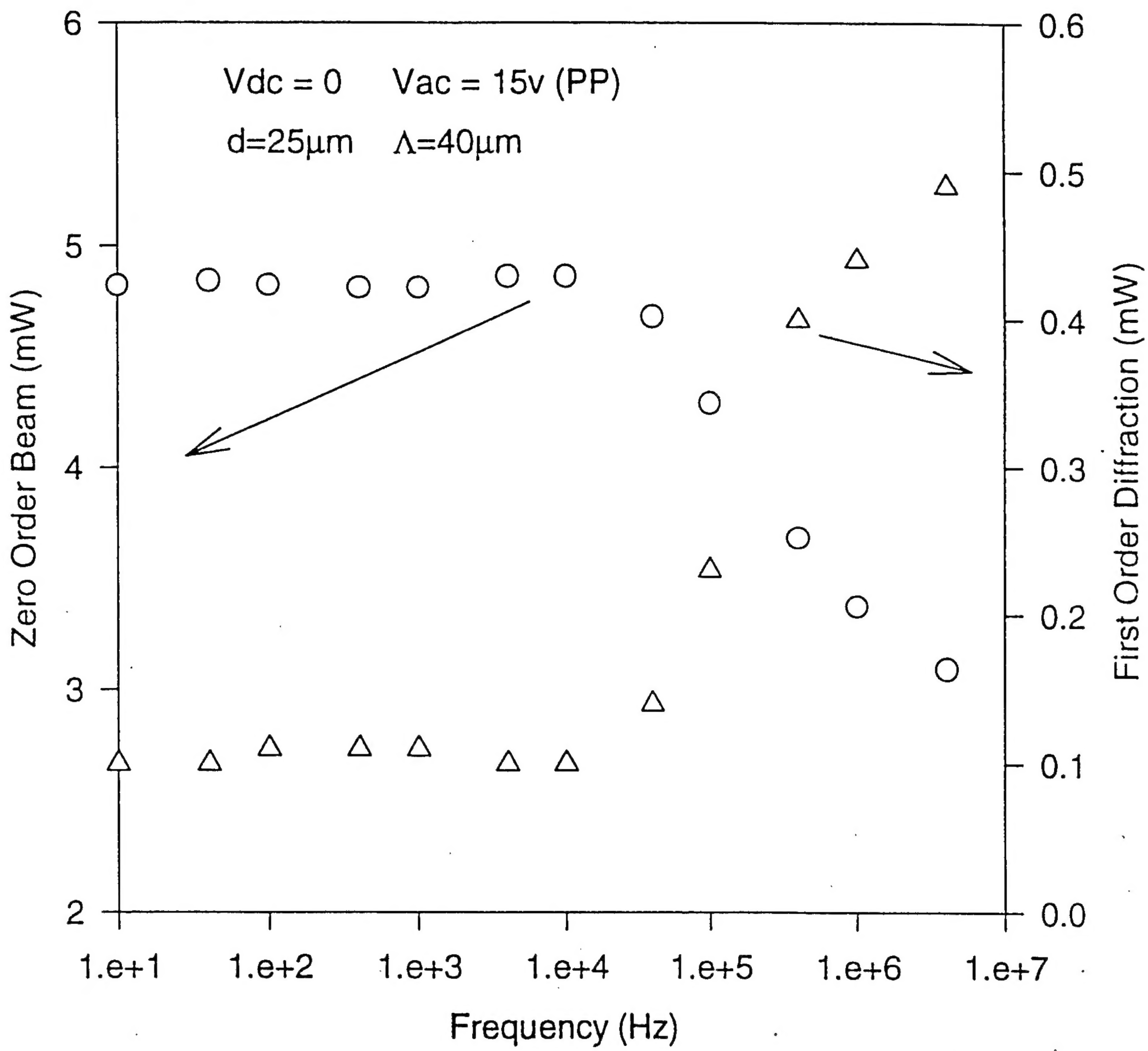


Fig.8 AC bias field frequency dependence of the diffraction efficiency from the permanent grating generated in a C60-doped nematic liquid crystal film.



" Liquid Crystalline Fibers Nonlinear Optics "

I.C.Khoo - Pennsylvania State University

ARO Grant #:- DAAH04-94-G-0061

· Results Highlights:

. Disvovered Photorefractive Effects in Nematic Liquid Crystal Films.
Obtained US Patent.

. Developed a quantitative theory for the photorefractive effect discovered.

. Developed a nonlinear fiber array device for optical limiting and image transmission application.
US Patent Application Approved.

. Demonstrated Optical Eye/sensor protection capability of Nonlinear Fiber Array against Nanosecond and Picosecond Laser Pulses.
Low Limiting Threshold and Clamping Level;High Dynamic Range.

. Identified and Synthesized Exceptionally Nonlinear Optical Liquids for use as Nonlinear Fiber Core.

. Developed quantitative theoretical modeling of core-moleular multi-photon and excited-state absorption processes and nonlinear guided wave optics.

Nonlinear Optics and Liquid Crystal Research Laboratory

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<u>Projects:</u>

I. Liquid Crystal Fibers and Fiber Arrays

- Nonlinear Ppropagation
- Optical limiting and sensor protection
- Optical switching, image transmissioon
- Frequency conversion; stimulated scattering

II. [Polymer-, Dye, C_{60}-,..] doped nematic Liquid crystal Films, Slab waveguides, .

- Photorefractive effects
- Optical phase conjugation
  self-starting;
  visible, diode laser, near IR [0.4 -1.5 mm]
- Electro-optical holographic gratings
- New lightvalve and modulators development.

III. Nonlinear Optics

- Dynamics of Optical Wave mixing
- Phase conjugation
- Nonlinear propagation, switching, limiting, nonlinear absorption, self-action, interface